Exploring smart grid possibilities: a complex systems modelling approach

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Exploring Smart Grid Possibilities: A Complex Systems Modelling Approach

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Abstract: Smart grid research has tended to be compartmentalised, with notable contributions from economics, electrical engineering and science and technology studies. However, there is an acknowledged and growing need for an integrated systems approach to the evaluation of smart grid initiatives. The capacity to simulate and explore smart grid possibilities on various scales is key to such an integrated approach but existing models – even if multidisciplinary – tend to have a limited focus.
This paper describes an innovative and flexible framework that has been developed to facilitate the simulation of various smart grid scenarios and the interconnected social, technical and economic networks from a complex systems perspective. The architecture is described and related to realised examples of its use, both to model the electricity system as it is today and to model futures that have been envisioned in the literature.
Potential future applications of the framework are explored, along with its utility as an analytic and decision support tool for smart grid stakeholders.

Keywords: Smart; Grid; Agent; Modelling; Simulation

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1 Introduction

Rising energy prices, climate change obligations and energy security concerns represent three powerful reasons why realisation of the smart grid concept is becoming a priority in many countries. However, complex social and economic factors have led to differing local perspectives. For example, in the EU the focus has been on the commitment to reduce carbon emissions and the concomitant infrastructure reinforcement costs. Many EU countries have policies to meet ambitious targets for CO_2 emissions reduction in the medium to long term, for instance the UK's Climate Change Act [1]. A key plank in the strategies to meet UK targets is electrification of heat and transport [2], which necessitates decarbonisation of the electricity system and implies increased capacity in the transmission and particularly the distribution networks. Higher penetration of renewable generators will play a significant role but the intermittency of direct solar, wind and other renewable energy is a source of complexity that causes problems in balancing the grid as their output cannot be adjusted on demand. Intermittency due to chaotic weather systems, when combined with non-linear feedbacks from multiple consumer and generator decisions in response to electricity availability and price, will lead to emergent system properties. In addition, as renewable generators can be deployed at various scales, including on-site or distributed generation (DG), the complexity attributable to interrelated temporal and spatial scales is increased.

Capacity increases on the network are expensive, as is large scale storage of electricity. It is estimated that the cost of accommodating proposed moves to electrically heated homes and electric vehicles in the UK using "Business as Usual" approaches (i.e. simply reinforcing the electricity network with more or bigger cables) would cost up to £36bn [3, Fig. 12]. The same study indicates that using smart grid techniques could reduce this cost by between £6bn and £25bn. The desirability of a strategy to use the existing infrastructure more intelligently, with minimal physical upgrading, is therefore economically evi-

Table 1: Comparison of the characteristics of conventional and smart grids.

Existing infrastructure	Smart grid
Central generation	Distributed and central generation.
Mainly dispatchable generation	Large proportion of poorly dispatchable generation.
Passive consumers	Active consumption, with quantity consumed changing in response to context, including a mix of automatic and manual control which requires behaviour change.
Basic meters providing total consumption with readings taken at billing intervals (typically three monthly)	Smart meters providing near real time consumption information.
Little dispatchability of demand	Dispatchable demand (Demand Side Response / Active Demand): distributed control.
Largely passive physical networks	Active networks (with communication), for example automatic tap-changing on transformers to stabilise voltage.
Hierarchical uni-directional power flow from central generator to distributed consumers	Bi-directional power and data flows.
High redundancy (extra cost)	Intelligent use of assets (cost savings) deployment of minimum assets based on sophisticated analysis of failure risk. Self re-configuring / healing networks.
Vertically integrated utility companies	Multiple supply business models including ESCos, MuSCos, etc.

dent. In the UK, this strategy motivates the development of the smart grid.

The particular characteristics of a smart grid are perhaps most easily described in contrast to a conventional electricity supply grid (Table 1). This table deliberately uses attributes of the smart grid which are generally accepted and does not focus on the contended definitions of smart grid which are apparent across different sectors. The implementations described later in the paper as an illustration of CASCADE's use focus particularly on examining the increased dispatchability of demand (Table 1, rows 3 & 5) and the reduced dispatchability of supply, and therefore required redundancy and cost, introduced by large renewables (Table 1, rows 2 & 8).

2 Complexity

With the introduction of active consumption and real time information, the smart grid introduces feedback between the consumer and the physical grid which has not existed hitherto. In order that the framework take this into account, adaptive consumption agents and market participants are included within the boundaries of the system to be modelled, alongside the physical grid and generators that have traditionally been studied when analysing electrical networks. The introduction of many active and interacting agents limits the applicability of traditional modelling as the agents are heterogeneous and exhibit non-linear feedbacks to information provided so are likely to lead to emergent properties. An example is illustrated in Figure 1, where consumers' on-off decisions provide a non-linear feedback based upon price via the physical network in the form of demand which is translated into price again in the market. Currently, the retail price is buffered from the effects of such feedback for domestic consumers, but this is envisaged to change as consumers react to real time information in the smart grid. This example captures just two of the multiple feedback loops that can occur between large numbers of interconnected agents at multiple scales in a fully smart grid. Other phenomena introducing complexity will exist, including the chaotic input of the weather via renewable generators and the potential introduction of localised collaboration to balance sub-networks at differing spatial scales.

Keeping power flowing requires continuous maintenance of a dynamic equilibrium between supply and demand in the face of demand that is reliant upon the vagaries of human action. In a smart grid future, the time series of supply and demand will exhibit emergent effects based on both chaotic inputs such as the weather and the

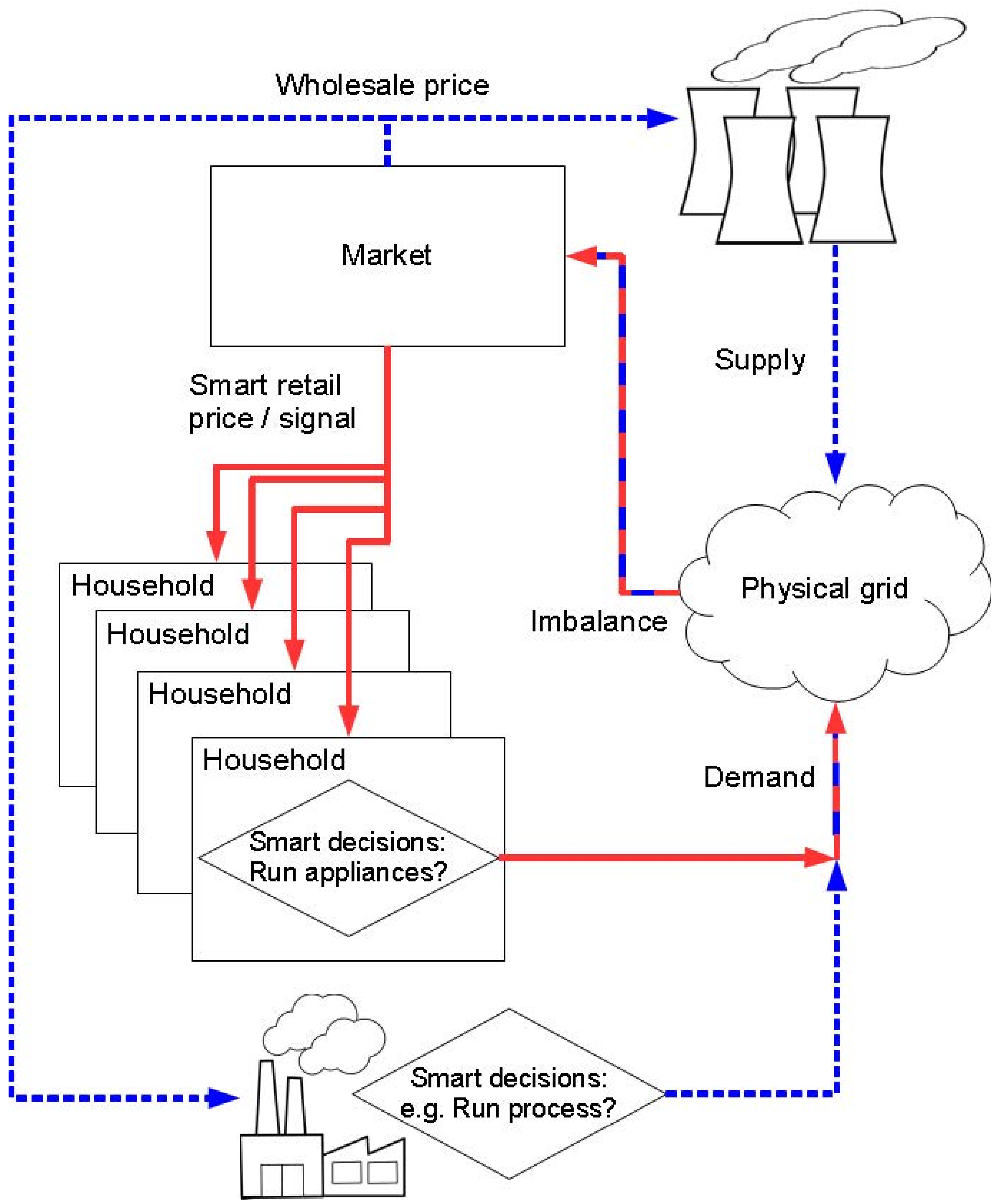

Figure 1: An example of two interconnected feedback loops in the smart grid – the red solid lines indicate retail price loop; blue dotted the wholesale price. Note that the feedback loops include real-time or near real time prices, inducing non-linear reactions

impacts of human behaviours, such as the frequently cited surge caused by large numbers of people switching on the kettle during the break in a popular televised event. The demand profile has traditionally been been met largely by relatively low latency, controllable generators, such as gas fired power stations. Increasingly, however, the supply side of the relationship is likely to exhibit similarly complex characteristics, with generators that are dependent on weather patterns at scales from the micro (< 5 kWp on domestic buildings) to the macro (wind farms with several GW peak generation). Weather dependence in the supply side introduces strong temporal variability, along with geographical correlation, in the peaks and troughs of generation. In addition, distribution of generation among many sites (for instance, micro generation on houses) subjects the supply of electricity to the potential effects of combined human agency with many tens of thousands of owners of small generators choosing how to deploy the electricity they generate.

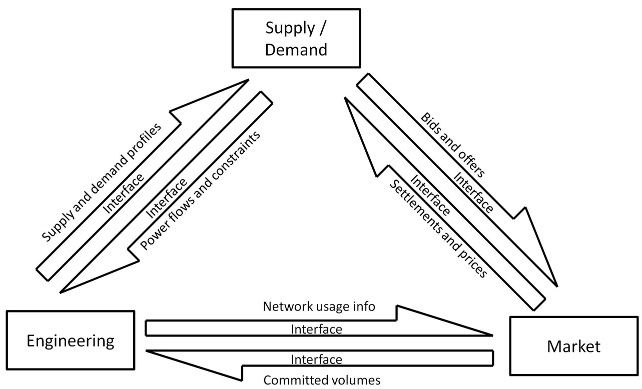

Figure 2: Overview of the three main modules of the CASCADE framework and the interfaces between them – labelled with the information that flows through the interfaces in each case

A useful way to characterise such a system is as a complex adaptive socio-technical system. Such a characterisation acknowledges the importance of the interaction between the social and the technical aspects of the system as well as the complex connections between components and the resulting complex system behaviour. Agent Based Modelling and Simulation (ABMS) is a methodology particularly suited to the analysis and exploration of such systems. In this methodology, agent behaviour is defined, as are the interactions between agents in the system under consideration and the environment within which they operate [4]. The overall system behaviour is not, however, pre-defined or characterised mathematically; rather it is allowed to evolve and be measured as the output of the model. ABMS is thus particularly useful when the objective of simulation is to observe the evolution of a system, adaptation of agents and the emergence of system level patterns or behaviour from the interaction at agent level. As [5, Sec. 2.1] report, according to Macal "The single most given reason [to use ABMS] boils down to... essentially the same thing: Agent-based models can explicitly model the complexity arising from individual actions and interactions that arise in the real world"

This paper describes the conceptual design and software architecture – but not coding particulars - of the CASCADE agent based modelling framework, which has been constructed to support the implementation of models for the investigation of possible smart grid markets and domestic smart control strategies [6]. Although intended to reflect details of the UK electricity system and government policies that affect it, experience reported by researchers in other countries has been considered in the design of the framework, particularly the AMES model, which has been mainly used to investigate market power in North America [7]; the EMCAS model, which has been used to model grids in some detail [8] with a main focus on power flow and the interaction with market pricing; and the NEMSIM model, which simulates Australia's electricity market with a strong focus on examining the carbon emissions from various scenarios [9, 10]. However, the CASCADE framework, is believed to be unique in its ability to capture the complexity likely to arise from the emergence of prosumers as significant market entities through the agency of advanced smart grid technologies. For a thorough survey of the use of ABMS in the electricity market, interested readers are referred to Weidlich & Veit [11] and Sensfuß et al. [12].

The description of the CASCADE framework's conceptual design is followed by two examples of its successful application and an outline of how it could be used to investigate further important smart grid issues with the potential to aid the decision making of smart grid stakeholders.

3 Conceptual framework and architecture

The framework is founded upon a description of the smart grid system as three inextricably linked modules: a Supply/Demand module, consisting of agents presenting supply and demand to the network based on their needs and capacities respectively; an Engineering module, consisting of a representation of the physical network; and a Market module, simulating wholesale trading of electricity. These modules interact with each other in feedback loops to determine overall system behaviour (Figure 2). Within each module, agents interact according to physical, economic and social rules.

The decision to partition the framework into three modules in its architectural design is based upon the differing techniques required to model each one. Although there is strong interaction between modules, with agents' behaviour affecting each, the characteristics of each module are distinct. For instance, the engineering module deals with complicated network structure and the engineering and mathematics of solving power flow equations, but consists largely of components with predictable physical properties (cables, transformers etc). In contrast, the market model has relatively simple structure, with complexity being introduced by the multiplicity of bids and offers that may be presented to the auction mechanism.

Models implemented within this agent based framework are specified by the behaviour of agents, the struc-

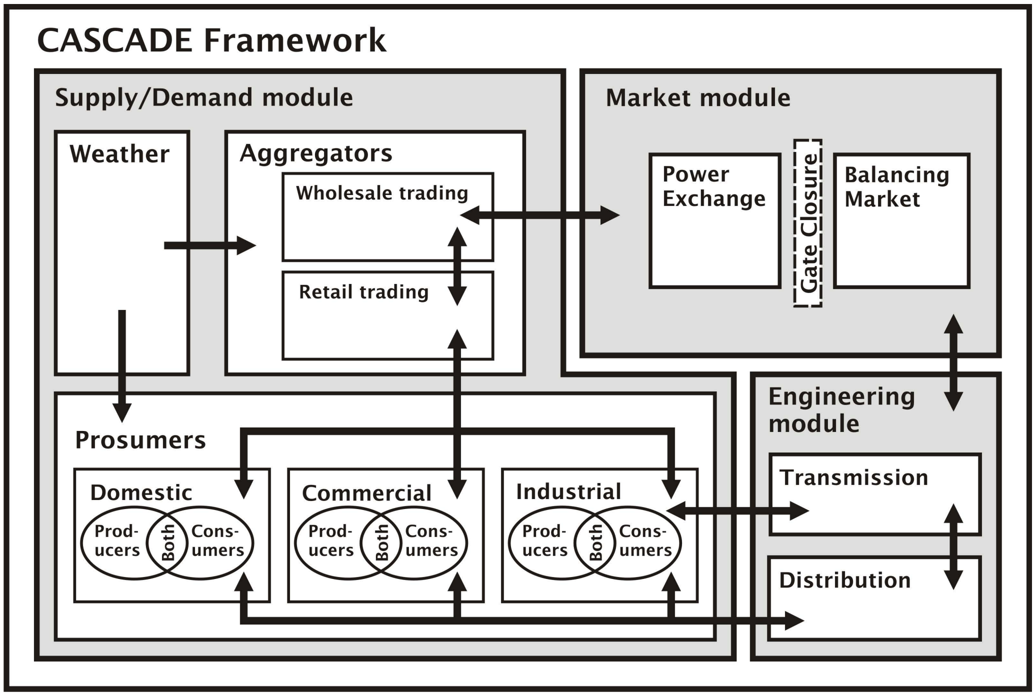

Figure 3: Detailed view of interactions between framework modules and agents

ture of their interactions and any relevant external inputs. The framework itself employs a modelling abstraction that categorises the vast majority of agents into two general classes – prosumers and aggregators. Prosumers represent an entity with a physical connection to the electricity network, which has the ability to change its behaviour over time, and presents a time-varying supply and demand to the system. An aggregator represents an economic entity that trades wholesale electricity on behalf of zero, one or many prosumers. The term aggregator is used with somewhat varied definitions within the smart grid literature. In the CASCADE framework, the aggregators are not constrained to be physical aggregators or Virtual Power Plants in the sense used in some of the engineering literature e.g. [13] , data aggregators as technical devices in the sense used in the smart grid communications literature [14], or corporate entities which take smart meter data and translate it into an aggregate usable form, such as third party service providers e.g. [15] or the Data and Communications Company specified by the UK government [16]. Using prosumers and aggregators in this way allows many differing views of potential future smart grids to be encoded, modelled and analysed. The specification of agents may be refined to varying degrees depending upon the scenario under scrutiny, as the examples given in this paper illustrate. Additional specialised agents may be added to the framework to perform specific tasks: however, the main adaptive agency in the model is within the prosumer and aggregator agents.

The framework is designed to impose as few mathematical constraints as possible on the agents within the model. The overall system behaviour is not governed by a mathematical model, but rather emerges from the behaviour of agents, which may itself be described by mathematical models (see section "Realised Examples"). The following relationships are enforced by the framework itself:

1. All prosumers must map to an aggregator – this is a many to one mapping function, f i.e. $f : P \to A$
2. Each agent must publish a net demand at each model timestep, where negative net demand is equivalent to net supply.
3. Each aggregator's net demand is the sum of the net demands of the prosumers mapped to it.

3.1 Module and agent interaction

Conceptually, prosumer and aggregator agents are situated within the supply/demand module and have a node representing their connection to the grid in the engineering model.

A major component of aggregator behavioural specification is the strategy that they use in placing bids and offers to the market in order to buy and sell wholesale power.

Figure 3 shows in more detail the interaction between modules within the framework and the agents within them. Arrows represent data flow and boxes functional elements within the framework.

The baseline implementation of the framework is written in Java, using the Repast Agent Based Modelling toolkit [17]. Environmental variables are provided to the agents via input files containing, for instance, weather data for the simulation time period.

4 Agent specification

The abstraction of agents in the smart grid system into the generic classes of prosumer and aggregator is an important feature of the CASCADE framework. This only specifies the characteristics shared by all envisaged agents within that class and the interfaces necessary for those agents to interact in each of the modules. These characteristics determine the minimum set of functions that any modelled agent must provide. Any model that is implemented using the framework must then specify variables and algorithms determining how these functions are calculated by any specific implementation of an agent. The set of variables and algorithms, which determine exactly how these functions are provided, may be as simple, or complicated, as the model requires. The following sections elaborate this through the provision of examples describing how existing agents map onto these abstractions and illustrate the potential for the abstractions to support the modelling of proposed future agents in the smart grid system.

4.1 Prosumers

Within the CASCADE framework, agents with a physical connection to the grid are implemented as Prosumer types. The term prosumer is becoming familiar in the literature discussing distributed generation and electricity networks e.g. [18, 19] and is used to reinforce the idea that any agent with a physical connection to the grid *could* (although is not required to) function as both a producer and consumer of electricity. This is an adoption of the general prosumer concept introduced by Toffler [20], which highlights the qualitative change when actors that had previously been pure consumers begin to participate in production. As more distributed generation is incorporated onto the electricity network (often retrofitted to existing domestic or commercial premises) the beginnings of such a transformation can be observed, as entities that had previously only consumed electricity gain the facility to produce it. It is expected that in smart electricity grids many prosumers will have both demand and generation capacity, making the prosumer abstraction particularly appropriate in the smart grid context.

The specification of prosumer agents requires only that they present net demand to the network at each time step. This high level specification does not preclude either of these being set to zero, in which case prosumers would behave as pure consumers or pure generators. Whilst such an implementation would represent the status quo arrangements within the electricity system and thus a baseline model, it deals with only the extreme cases along the prosumer continuum. In general, a prosumer would have both a demand and supply profile and may have the capability to shift the quantity of electrical energy that they consume or produce over time in response to influences from other agents or their environment. The capability to alter the timing of supply is standard in conventional generation and is referred to as dispatchability. However the widespread ability to shift demand in time, particularly amongst domestic or commercial actors, is emerging and referred to as Demand Side Management (DSM) or Demand Response. Such a capability is discussed in the literature, with consideration given to both demand deferral e.g. [21, 22] and storage e.g. [23]. Roscoe and Ault [24] summarise current discussions and open questions with regard to DSM, incorporating questions of storage and load shifting. There has been relatively little work that utilises a bottom-up model of demand management within this theoretical framework, abstracting storage and demand deferral to simply time-shifting demand, which may be either positive or negative from the *a priori* intended time of use.

A number of typical implementations of prosumers are outlined in Table 2. The list is not intended to be exhaustive, but rather to demonstrate the flexibility of the framework to be extended and represent a full range of grid-connected entities. It can be seen that some implementations are pure generators or consumers (having zero demand or supply respectively), whilst others represent the diverse array of prosumers often envisaged in a smart grid future.

4.2 Aggregators

An aggregator is an entity that represents a group (or aggregation) of any number of prosumers and other aggregators by summing the demand and supply of all its customers and trading these to satisfy its corporate objectives.

Table 2: Selected examples of specific prosumer implementations

Real world entity	Demand profile	Supply profile	Behavioural
Conventional thermal power stations (coal, gas or nuclear fuelled)	Not significant in most applications	Function of plant ramp rate and min/max capacity	Responds to the direction of its representative aggregator
Wind farm	Not significant in most applications	Function of weather	No behavioural adaptation – aggregator bids on the basis of non-dispatchable generation
Solar park	Not significant in most applications	Function of weather	No behavioural adaptation – aggregator bids on the basis of non-dispatchable generation
Household	Function of weather, occupancy, and stochastically generated preferences (e.g. for appliances or electric vehicles) and behavioural algorithm	Function of generation equipment ownership, behavioural algorithm and weather	Human behavioural model of reaction to electricity price. May include a model of technology adoption
Household with smart control	Function of weather, stochastically generated preferences and behavioural algorithm	Function of generation equipment ownership, behavioural algorithm and weather	As above, with the addition of a smart controller which reacts to a smart signal to place controllable demand optimally within a time window
Commercial office	Function of typical office hours and temperature	Typically zero, may be function of weather if tenant has ownership of some renewable generation	Typically temperature regulated by a Building Energy Management System (BEMS). May be modelled to react to smart signal
Industrial load	Function of specific industrial process being undertaken	Typically zero, may be function of weather if some renewable generation	May be able to move some large loads in time (e.g. defer a heating process until the night time), but demand determined by industrial process

In turn, the aggregator offers supply of electricity to its prosumers (or subsidiary aggregators). At the highest level of abstraction, the decision making process by which the aggregator conducts its trading in the model is not predetermined and the flexible specification of these in any implementation of a simulation is part of the value of the framework.

Aggregators typically represent utility companies, Energy Service Companies (ESCos), Multi-Utility Companies (MUSCos), Community Energy Service Companies (CESCos), etc. They could also include non-physical traders of energy (e.g. futures traders) who represent a boundary case for the aggregator class of agents, being connected to zero prosumers and operating simply as a commercial entity with a target of zero net supply and demand. Table 3 describes some of the more commonly described entities, both extant and proposed, and how they would be mapped onto the CASCADE framework in order to model and analyse a smart grid scenario containing some or all of them.

The definition of the term aggregator is not a settled one in the smart grid literature. The broad interpretation of an aggregator as 'a commercial entity representing a number of prosumers', employed within this framework, allows for a wide variety of entities to be specified as particular implementations of the aggregator class of agents. Such implementations may include aggregators that are rather similar to the data or physical aggregators referred to in other literature e.g. [13].

Network operators may be seen as physical aggregators, but in alignment with UK energy market regulation [25, Para. 30], CASCADE treats these as distinctly different entities and, for clarity, retains the definition of Network Operators to refer to them. Both the Transmission Network Operator (TNO) and Distribution Network Operators (DNOs) reside in the Engineering Module of the CASCADE model. This distinction does not, however, limit the flexibility of the framework as one-to-one mappings of DNO to supply companies can be made if the framework is to be used in scenarios where those entities are matched.

5 Realised examples

The CASCADE framework has been used to investigate a number of smart grid scenarios including domestic demand response in presence of increased renewables [26, 27], UK Market with high wind penetration [28], Micro-grid simulation in presence of renewable generation [29], a practical application demonstrating demand shaping [30], Macro impacts of wind [31] and domestic adoption of PV and smart controllers [32, 33]. Two example uses are reported here to illustrate the potential of the framework to yield insights into important smart grid issues and to explore new mechanisms for exploiting smart grid opportunities. In the first, the likely impact of a high penetration of large scale wind generation on the UK short term electricity market is investigated [28]. In the second, the potential for a smart electricity supply company to perform demand side management by shaping the demand profile of its prosumer base is explored [26, 34].

5.1 Effects of intermittent wind generation on electricity markets

The effects of intermittent, non-dispatchable renewable generation (such as wind farms) on electricity markets is of paramount interest among the research community due to its complex nature and to the rapid penetration of renewable generation into the electricity grid. Agent Based Models have previously been used to investigate wholesale electricity markets [7, 9], e.g. [35, 36], exploring, for instance, the potential for manipulation of wholesale markets by electricity suppliers [37]; the potential for large fluctuations in marginal price under certain conditions [38]; and the coupling of retail and wholesale markets in the smart grid [39].

An Agent-Based Short Term Electricity Market (A-STEM) module was developed for the specific purpose of investigating the effects of varying energy supply mix on the short term UK market. This module comprised various trading entities such as the Balancing Mechanism Units (BMUs) that represent both the generating and demand sites. The generators were further categorized into large scale conventional agents such as coal or CCGT (Combined Cycle Gas Turbine) power stations alongside large scale wind generators (parameterised as described in Table 3). The A-STEM module was integrated within the CASCADE framework by representing the BMUs as aggregators. These aggregators then participate in a short term electricity market designed around a simple power exchange, implementing a discriminatory double auction, followed by a balancing mechanism market. The aggregators bid and offer in these markets based on their current supply and demand profiles and the estimated imbalance in the entire system. They repeat this procedure based on historical experiences and their own forecasts, using the Roth-Erev reinforcement learning algorithm [40] to adapt their bid and offer strategy over the course of the simulation. With reinforcement learning, after each round of bid-

Table 3: Selected examples of specific aggregator implementations

Real world entity	Represents which agents		Behavioural strategy
	Type	Typical number	
Business-as-usual utility supply company	Household, commercial and industrial prosumers	10,000+	Maximise profit, based on quantity of energy supplied to customers and price paid on wholesale market
Smart utility supply company	Household, commercial and industrial prosumers	10,000+	Receive smart metered data from prosumer base, combine with commercial data and transmit a smart signal to influence or control prosumer supply and demand
Large conventional generation company	Conventional generation prosumers	1 – 10	Maximise profitability of generation based on plant ownership
Vertically integrated umbrella company	Other aggregators	5 – 10	Seeks to maximise profit by implementing strategies to either balance supply and demand within its portfolio or sell on the open market
Small energy supplier	Household, commercial and industrial prosumers, alongside meso or macro scale renewable generation prosumers	1,000+	Maximise profitability of supply to small number of prosumers. May seek to appeal to a niche market, such as those wishing to buy exclusively renewable energy
Energy service company	Household, commercial and industrial prosumers	1,000+	Seek to minimise energy input to deliver a particular contracted service, for instance the provision of heat. May invest in efficiency measures for its prosumer base
Community generation company	Meso-scale generation plant prosumers – usually renewable although could encompass	100+	Deliver maximum benefit to owning community. May implement various strategies e.g. try to balance supply and demand locally before trading on open market. May utilise profits for community projects CHP also
Macro renewable generation company	Wind turbine prosumer, solar park prosumer	1+	Offer generation at a price to both maximally utilise plant and maximise profit
Virtual Power Plant	Domestic prosumers, community generation prosumers or aggregators	100+	Bid the generation of a large number of small distributed generators as if they were a large power plant, maximising benefit for itself and its prosumer base
Local monopolistic supplier	Households, offices, industrial, small scale generation prosumers	1000+	Dual objectives of a DNO and supply company – to optimise utilisation of the physical infrastructure and maximise profitability of supply

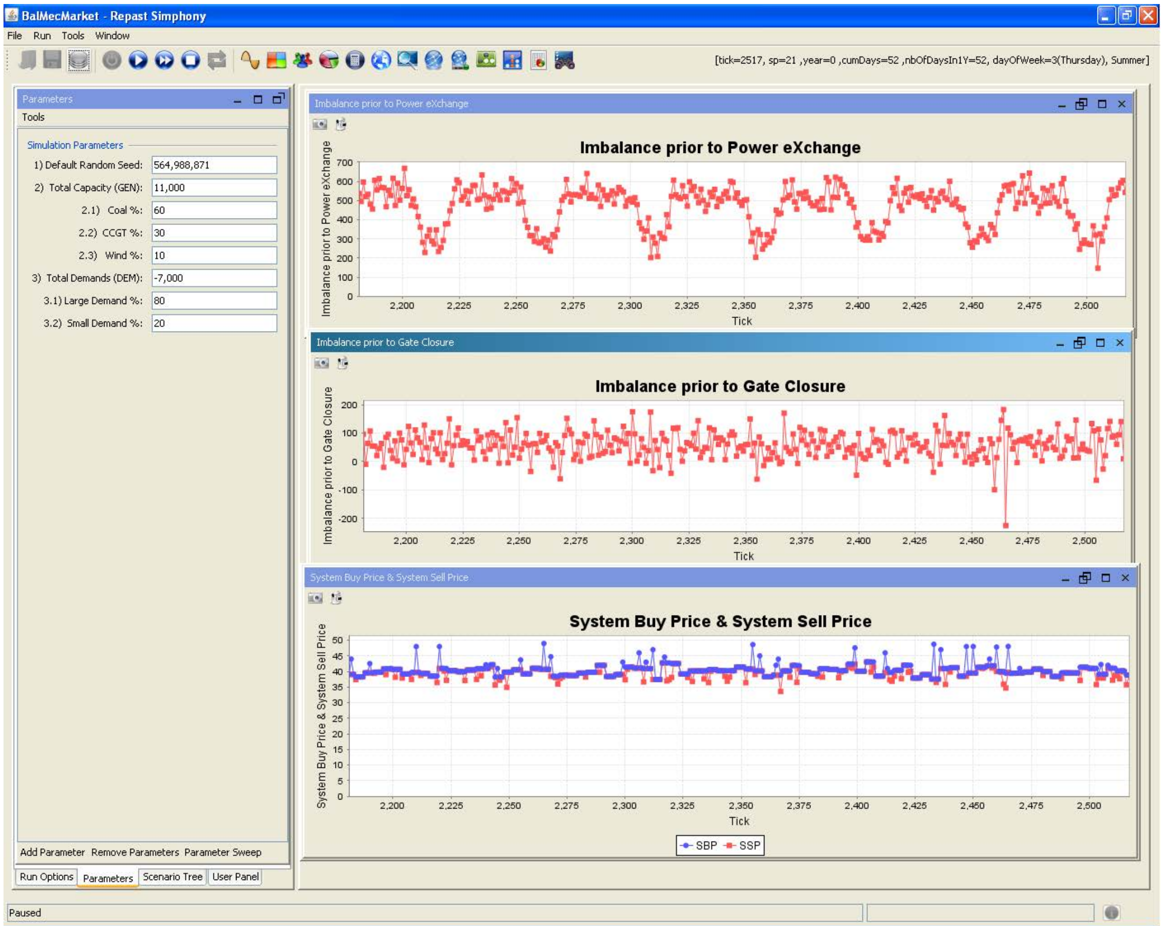

Figure 4: Screenshot taken from the market simulation illustrating the power imbalance prior to exchange (top); imbalance prior to gate closure (middle) and the system buy and sell prices (bottom)

ding, the agents update the propensities of submission for a given bid/offer *i* by

$$q_i(t+1) = q_i(t) + x$$

Where q_i is the propensity to re-submit bid/offer i and x is the payoff from submitting that bid/offer. The Roth-Erev algorithm then updates probabilities of re-submitting each bid/offer in the next round as follows:

1. When calculating the propensities, multiply x for a successful bid by (1-ε) and all other bids by ε to encourage experimentation.
2. Multiply each propensity by (1-φ) where φ is known as the recency, or forgetting, factor and ensures that very old results do not make recent results irrelevant to outcome.
3. Normalise the propensities to give probabilities:

$$p_i(t) = q_i(t)/\Sigma q_j(t)$$

4. If the probability is below a threshold μ, set it to zero.

The A-STEM module was implemented with additional specialised agents: a system operator agent who oversees the balance of supply and demand and also deals with the bids and offers of the aggregator agents; a power exchange agent to operate the auction; and a settlement company agent to settle the power market. Finally in this use of the framework, a message board object that displays the appropriate level of information for all the other agents is incorporated in the model. The proportion of supply from wind generators was an initialisation parameter for this particular implementation. The proportion of wind generation was increased over a number of simulation runs, the market imbalance and resulting system buy and sell prices were measured and the volatility of those prices analysed (Figure 4). A high penetration of wind generators, with a constant total generating capacity across all types of generators, was found to increase the range and volatility of the system sell and system buy prices. This suggests a requirement for further exploration into different trading strategies for such generators or a possible re-

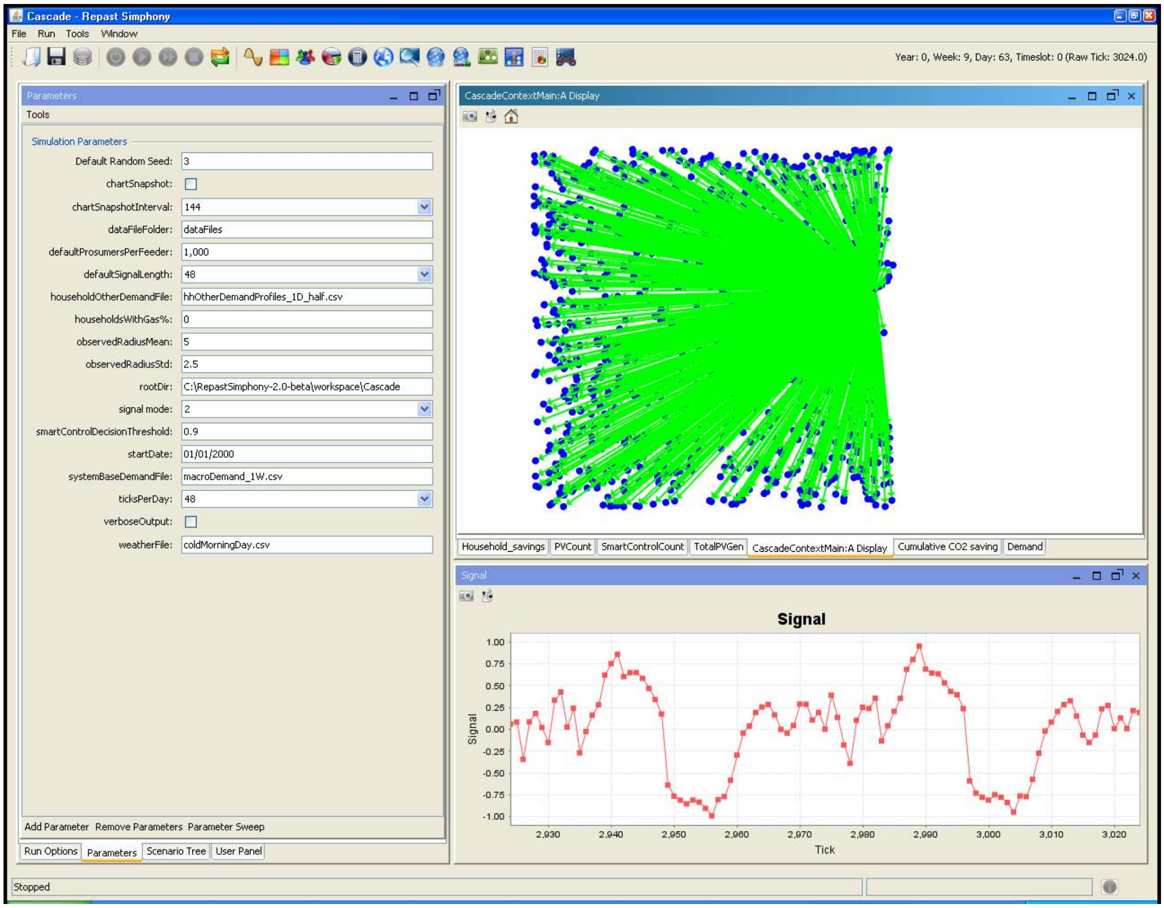

Figure 5: Screenshot of CASCADE framework configured to model dynamic demand response. The left pane in the simulation window shows parameters for this run, the top right the configuration of the economic network linking the aggregator to its prosumers and the bottom right the signal transmitted across that network.

designing of the market structure and cash-out prices. The results shown as a result of this analysis have far reaching consequences for smart grid strategies which rely on the short time wholesale price to indicate the desirability of consumption. The UK is currently undertaking a process of Electricity Market Reform within which one of the proposals under consultation [41] is localised pricing of wholesale electricity. The above analysis can shed light on the potential consequences of such a scheme and provide information on its merits to inform decisions.

5.2 Smart demand side response

The ability to manipulate the demand profile seen on the electricity network is one of the major objectives of the smart grid. A number of strategies have been proposed to do this, including variable tariff schemes such as those reviewed by Faruqui and Sergici [42], fine grained auctioning of all power consumption e.g. [43] and smart control strategies e.g. [24, 44]. The CASCADE framework was used to model a relatively small group of household prosumers in a proof-of-concept simulation to investigate how an electricity supplier might achieve demand side management using a signal to influence the demand profiles of its customers. A single aggregator was defined with a prosumer base of 1000 household prosumers, each having a single connection to the aggregator in an economic network (Figure 5 – top right). In this scenario, all the household prosumers in the model were endowed with a smart controller which was allowed to allocate a portion of the household's electricity demand in response to a signal indicating on a continuous scale the desirability or undesirability for demand to occur at any time over the next 24 hours. The aggregator in this implementation was configured to initially send a null signal and measure the overall demand in order to learn the baseline consumption profile of its consumer base (Figure 6). Following the baseline measurement, the aggregator sent a training signal (see [27] for details) and again measured demand to construct a model of

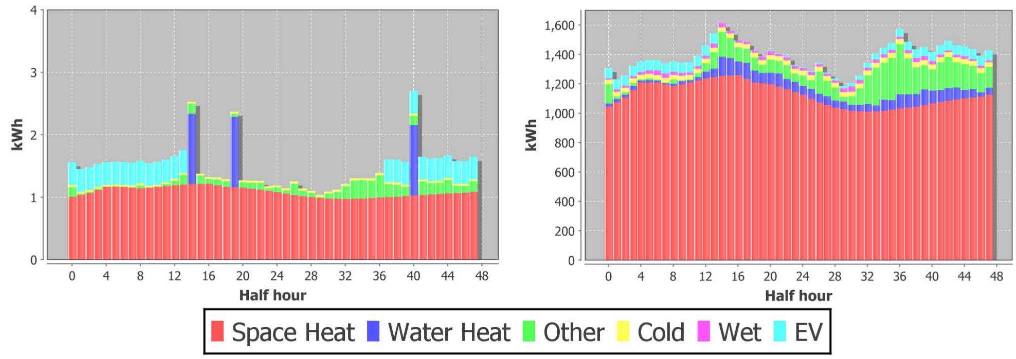

Figure 6: Screenshot showing baseline demand profiles for an individual household (left) and aggregated across all households (right) for a single day at the start of a simulation run.

how the smart controller equipped consumer base would respond in aggregate to a signal at each time of day. Finally, the aggregator uses this model with a non-linear optimisation algorithm (in this case Nelder-Mead Simplex) to construct a signal (e.g. Figure 5 – bottom right), which, when sent to the aggregator's entire customer base of prosumers, will achieve an aggregate demand profile that is as near to flat as possible. i.e. the Nelder-Mead optimisation calculates signal values Si for each half hour of the day i, such that

$$\Sigma D_i / D_{ave}$$

is minimised, where

$$D_i = B_i(1 + S_i k_i) + c_i$$
$$-1 \le S_i \le 1 \text{ for } i = 1 : 48;$$

D_i is the aggregator's prediction of demand in a time slot across its consumer base given that it sends a signal S_i k_i and c_i characterise a linear model of that consumer base in a given timeslot and are learnt during the training signal period above.

The demand side management scheme modelled in this scenario demonstrates the implementation of an aggregator with a complicated behavioural specification that changes over time between three regimes of operation. The capability to implement such a rich agent is one of the framework's important features.

This model exploits a second important feature of the framework: widespread heterogeneity in the initial conditions for a simulation run. The households were initialised with stochastically generated, statistically representative occupancy, building characteristics and appliance demand profiles (Figure 6). The ability to easily initialise relatively large numbers of agents, with heterogeneous and statistically representative characteristics, is useful when simulating populations for which individual data is unknown but a spread of possible outcomes is needed for a population where bulk characteristics are known or can be estimated.

The prosumer agents implemented in this scenario demonstrate the richness of behaviour that can be incorporated within a model implemented using the framework. The smart controllers modelled in each household prosumer agent used algorithms that could

- switch off the space heating in the individual household for a short period without altering the thermal comfort of the occupants (temperature restricted to $+/-0.5°$C from desired);
- switch off cold appliances for short periods (one half hour timeslot);
- shift water heating and shift wet appliance loads in time.

Other demands such as lighting or use of the television are deemed uncontrollable by the model developer and so are unaffected. The net result is that the controlled loads within the household (water heating, space heating and electric vehicle charging) are moved from periods of high demand to use electricity overnight where there was a "trough" in baseline demand. This results in lessened variability in the aggregate profile across the day (Figure 7).

This scenario demonstrates the framework being used to produce a proof of concept model for a particular smart grid strategy at local household level. The ability to send a universal signal to a group of prosumers to flatten demand (or provide demand shaped to make use of renewable generation) is one that would be highly useful to supply companies in a smart grid. This model demonstrates that possibility through smart controllers reacting in proportion to such a signal across the aggregator's prosumer base.

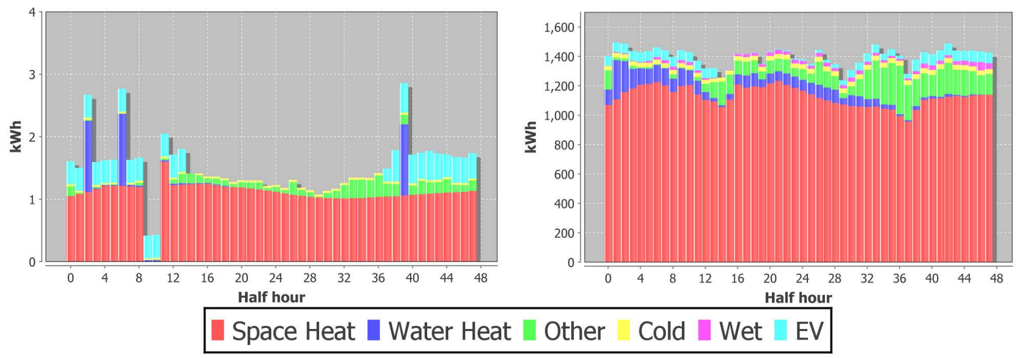

Figure 7: Screenshot showing baseline demand profiles for an individual household (left) and aggregated across all households (right) into a flatter profile at the end of a simulation run.

6 Scope of Use

This section expands upon the scenarios highlighted in the previous section to illustrate the flexibility and potential of the CASCADE framework to support further investigations into important smart grid issues and possibilities that have received attention in the academic literature and in policy documents. It is appropriate to delineate a large number of what-if scenarios in the context of the emerging smart grid and associated technologies and policies; these suggestions should not be interpreted only as snapshots of work in progress and further work by the authors but rather as a panorama of opportunities for complex systems studies enabled by the CASCADE framework in a relatively new and rapidly expanding field.

The expansion of the demand response scenario to include simulation runs with changing characteristics of equipment ownership in the prosumer base is the already the subject of ongoing work [33]. There are further opportunities to refine the scenario to include the broadcasting of different signals to particular groups of prosumers, or to introduce multiple aggregators with various prosumer bases and objectives. Differing levels of penetration for smart controllers, electrical heating and electric vehicles might also be explored.

The market investigation scenario can be expanded to include a reserve market that operates hours before market closure or to enrich the description of the aggregators to include more realistic costs of production and geographical location on the physical network. In addition, the two scenarios can be coupled together, with a smart utility aggregator bidding its adaptable (partially dispatchable) demand on the wholesale market alongside the generation aggregators. Work towards such a model is underway.

In addition to the scenarios described above, there is work in progress to investigate the effect of different assumptions about the behavioural and learning strategies of agents on system evolution alongside the likely adoption of technologies under various policy environments. These lines of research will contribute toward an understanding of the behaviour observed in current smart grid tests and pilots. They may also shed light on the success or failure of policies designed to incentivise the uptake of technologies that are essential for the operation of the smart grid (for instance renewable generation, smart controllers, electric vehicles, electrical heating and so on).

Other possibilities include studies of the influence of social networks on demand profiles across household prosumers and the full interconnectedness of the social network with the economic and technical systems present rich fields of research. The potential for large-scale industrial DSM could be explored [45], where response from commercial and industrial prosumers may yield far greater rewards from fewer agents than a similar approach at the domestic level. Finally, the interconnection of the electricity grid with other energy infrastructure networks, for instance proposed Hydrogen networks via grid-to-fuel processes [46], offer considerable opportunities for future research using the CASCADE framework.

7 Conclusion

The likely evolution of the smart grid as a complex system has been described and the utility of the CASCADE framework in providing a new and flexible environment for modelling a wide range of smart grid scenarios demonstrated. The structure and functionality of the framework have been explained and examples given of its scope, including two extended examples describing firstly a model of complex electricity market behaviour in different wind power penetration scenarios, and secondly the development of a novel distribution network based scheme for smart demand response. The examples represent models and applications at different scales and demonstrate in particular the power of the CASCADE modelling abstractions for prosumer, aggregator and other electricity market entities, which allow different levels of specification to be implemented within the same framework. Example models and their mathematical basis have been described, however a wide range of mathematical descriptions of agent behaviour within the framework are possible. This flexibility means that the framework can be used to address different classes of problems, such as proof of concept for technical solutions to specific smart grid issues and opportunities, provision of insight into more speculative smart grid possibilities, entities and effects, and bottom-up investigation of top-down policy implications and consequences in the face of complexity.

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